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Research Article

Integrating nature-based solutions in estuary management: A climate mitigation perspective from Demak, Central Java

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Abstract

Estuaries are vital ecosystems that play a crucial role in mitigating the impacts of climate change. They act as natural buffers against rising sea levels and coastal erosion while serving as significant carbon sinks due to their diverse and productive ecosystems. Integrating Nature-based Solutions (NbS) into estuary management offers a promising approach to mitigate the impacts of climate change while enhancing ecosystem services and community resilience. This study focuses on the potential of NbS in managing estuaries in Demak, Central Java, a region highly vulnerable to coastal hazards such as erosion, flooding, and land subsidence. Key strategies explored include mangrove restoration, sustainable aquaculture, and community-driven conservation efforts. The findings demonstrate that these approaches can reduce the risks associated with climate change, improve biodiversity, and support local livelihoods by providing sustainable economic opportunities. Mangrove restoration in Bedono Village, Demak, illustrates how Nature-based Solutions (NbS) and hybrid engineering can address coastal subsidence, tidal flooding, and ecological degradation. Field observations (2022–2025) show that mangrove rehabilitation supported by permeable brushwood barriers has increased sediment accretion by 5–15 cm/year and enabled natural recruitment of Avicennia and Rhizophora, contributing to shoreline stabilization. Community-led restoration achieved estimated mangrove survival rates of 60–70%, while participatory activities involving youth and women strengthened local livelihoods and environmental stewardship. Comparative analysis with other Indonesian and regional projects highlights the effectiveness of integrating community engagement with low-cost engineering. The Bedono model demonstrates the potential of NbS to enhance coastal resilience, support carbon sequestration, and align with national climate strategies, offering a replicable framework for vulnerable estuarine regions.

Key words: Nature-based Solutions, estuarine management, climate resilience, Demak, mangrove restoration, sustainable aquaculture, Bedono

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Introduction

Estuaries, the transitional zones where freshwater rivers meet marine systems, are among the most productive and ecologically significant environments on Earth (Stamp et al. 2022). They support over 1,500 marine species during crit-

ical life stages and provide vital ecological services such as nutrient cycling (Hoshovsky et al. 2025), carbon storage (Yang et al. 2025) and shoreline stabilization (Spiering et al. 2021). Estuaries buffers against climate change impacts such as coastal erosion, sea-level rise, and extreme weather events (Hülsen et al. 2025). Intertidal ecosystems such as salt marshes can dissipate wave energy and reduce erosion and flooding (Van Coppenolle and Temmerman 2019), while mangroves provide natural coastal protection through wave attenuation and sediment controll (Osland et al. 2022; Verutes et al. 2024).

In addition to ecological function, estuaries provide socio-economic benefits. They act as vital nursery grounds for many marine species (Priya et al. 2022; Inness-Gold et al. 2025), tourism (Jones et al. 2023), contribute to water filtration (Ward et al. 2023), and maintain biodiversity (Dowdall et al. 2022). Despite their importance, estuarine ecosystems face growing threats from land subsidence (Pedretti et al. 2024), deforestation, and unsustainable aquaculture (Van Wesenbeeck et al. 2015; Nagaraju et al. 2025), pollution, and infrastructure development.

Mangrove are particularly critical components of Indonesia estuaries due to their capacity for carbon sequestration and coastal protection. Indonesia contains approximately 22.6% of the world's mangrove area (Giri et al. 2011; FAO 2023) and harbours more than 50 mangrove species, predominantly of the genus Rhizophora (Arifanti et al. 2022; Martin et al. 2024; Suhardi et al. 2024). Yet, Indonesia remains among the countries with the highest mangrove deforestation rates, contributing significantly to greenhouse gas emissions and biodiversity loss.

Nature-based Solutions (NbS) offer a sustainable approach to restoring and managing estuarine ecosystems by leveraging natural processes to enhance resilience (Rahaman et al. 2020), and provide multiple benefits for biodiversity, climate resilience, and human well-being (Baustian et al. 2020; van der Meulen 2022; Filz et al. 2025).

The International Union for Conservation of Nature (IUCN) defines NbS as actions that protect, manage, and restore natural ecosystems to address societal challenges while supporting biodiversity and human well-being (Huera and Davis 2023; Berg et al. 2024; Chairat et al. 2024).

This study examines the integration of NbS in estuarine management in Demak, Central Java, a region experiencing severe coastal abrasion. The research evaluate the effectiveness of mangrove restoration, sustainable aquaculture, and community-driven conservation initiatives in mitigating climate change impacts while supporting biodiversity and local livelihoods. The study focuses on the application of NbS in Bedono Village, Demak, Central Java, where mangrove degradation and coastal erosion have severely impacted both the environment and livelihoods.

Mangroves are a prime example of NbS, providing numerous ecological benefits such as carbon sequestration, coastal protection, and habitat for biodiversity (Lovelock et al. 2024; Yang et al. 2025). Effective conservation policies can protect these ecosystems from threats like habitat destruction, pollution, and climate change impacts (Jayakumar et al. 2024; Waleed et al. 2025).

Bedono, a coastal village in Demak, is among the most vulnerable areas, having lost significant land to tidal inundation and environmental degradation. The phenomenon known as "Rob," which is caused by tidal fluctuations, has severely impacted the village. The inundation patterns, particularly from April

to June, reach heights of 50–110 cm and cover an area of 12.7 km², disrupting community activities, livelihoods, transportation, and social structures. This has led to a cultural adaptation where the community has developed unwritten rules and behaviors to cope with the recurring tidal floods (Setyawati et al. 2017). The community relies heavily on fisheries and aquaculture, which are increasingly affected by coastal hazards (Hague et al. 2021; Rani 2025). Previous interventions, such as mangrove rehabilitation and sediment traps, have shown potential in reducing coastal hazards (Utami et al. 2024). However, in the long term, sustainable solutions are still required to ensure the resilience of local communities and ecosystems (Foti et al. 2020; Gupta et al. 2025).

Methods

Study area

The study was conducted in Bedono Village, Sayung Sub-district, Demak, Central Java (6°55'–6°57'S, 110°30'–110°33'E), an area severely affected by coastal erosion and land subsidence. Bedono functions as a living laboratory for NbS, including mangrove rehabilitation and silvofishery systems.

Research approach

A mixed-methods approach was employed to comprehensively assess the implementation and ecological outcomes of NbS in Bedono Village, integrating both qualitative and quantitative data collection techniques (Amiron et al. 2024; Ramírez et al. 2025). This approach was chosen to capture the complexity of the ecological, spatial, and social dimensions associated with coastal restoration and climate adaptation. Bedono Village was selected as a focal site due to its high vulnerability to tidal flooding, land subsidence, and coastal erosion (Marfai 2012; Rudiarto et al. 2018). The methodological framework combined document review, field observations, ecological monitoring, stakeholder consultations, and participatory assessments.

Secondary data were obtained from government reports, including the Ministry of Environment and Forestry's FOLU Net Sink 2030 roadmap (MoEF 2023), and peer-reviewed studies on mangroves and coastal adaptation (Murdiyarso et al. 2015; Muskananfola et al. 2020; Sasmito et al. 2020). Existing ecological monitoring datasets were incorporated from NGOs and academic partners (Soeprobowati and Hariyati 2017; Prasetyo et al. 2024).

Field observations and environmental monitoring

Field data were collected during two contrasting seasonal periods, representing the wet season (March 2025) and the dry season (October 2025), to capture seasonal variability in hydro-ecological conditions. Sampling was conducted across three main sites within Bedono Village—Bedono, Pandansari, and Morosari—selected to represent gradients of mangrove restoration activity and tidal exposure.

Field observations were conducted at multiple locations within Bedono Village (Fig. 1). to document restoration interventions and ecological conditions.

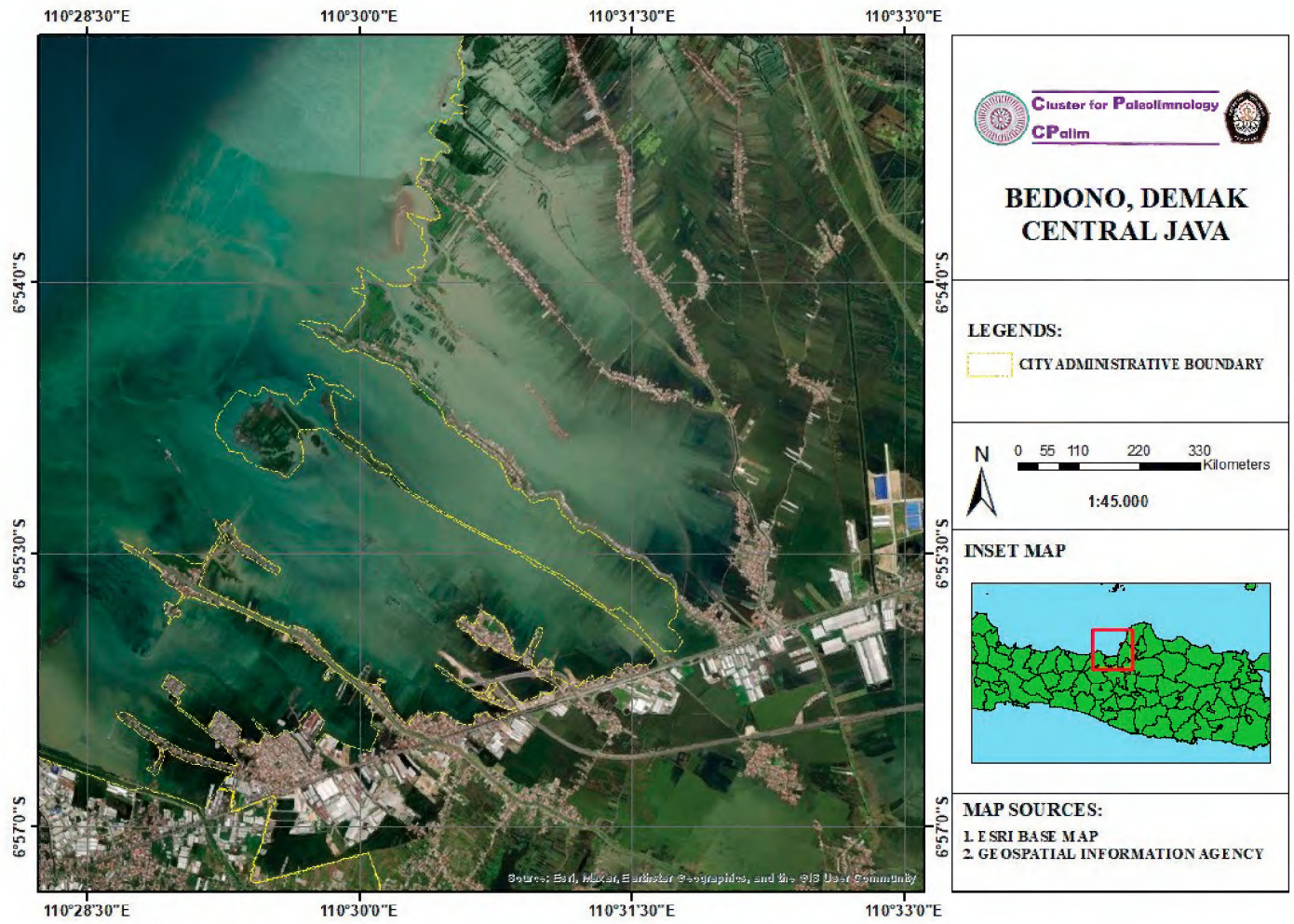

Figure 1. Georeferenced Satellite Imagery of Bedono, Demak, with Administrative Boundaries and Inset Location Map.

Quantitative environmental parameters were measured systematically, including soil, water pH, salinity, and sediment texture, using portable digital meters and standardized sampling protocols. Salinity and pH were measured *in situ* using a YSI multiparameter probe at five monitoring stations during the dry and wet seasons of the same year. Each value represents the mean ± standard deviation (n = 5).

Vegetation and sediment accretion

At each site, three 50-m transects were established perpendicular to the shoreline, with three 1×1 m quadrats placed at 0,25, and 50 m along each transect (27 quadrats per season). Mangroves were identified to species level, and stem density, seedling regeneration, and canopy condition were recorded. Dominant species included *Avicennia marina*, *Rhizophora mucronata*, and *Sonneratia alba*. Seedling survival was assessed from tagged individuals between surveys. Sediment accretion was measured using 1.5-m PVC stakes and marker horizon techniques (Cahoon et al. 2002).

Socio-economic data collection

Primary socio-economic data were obtained from the Bedono Village Office (2024), which maintains annual records on population displacement, housing loss, and mangrove planting programs. For example, the reported rate of housing loss (≈approximately 30 houses per year) was derived directly from these village records, verified through field observations and participatory mapping with local leaders (*Kepala Dusun*). Additionally, semi-structured interviews were conducted with 20 respondents representing key community groups, including fishpond owners, women's cooperatives, youth associations, and village offi-

cials. Interviews explored perceptions of mangrove restoration, economic diversification (e.g., products derived from mangroves), and local governance in the implementation of NbS.

Community participation and perception assessment

Structured interviews and participatory workshops captured local knowledge, perceptions, and participation in NbS initiatives. Standardized questionnaires explored awareness of climate impacts, attitudes toward mangrove restoration, and perceived benefits of ecosystem-based adaptation. Field observations were supplemented by focus group discussions with fisherfolk, women's groups, and village leaders (Morales et al. 2024; Utami et al. 2024). Participatory workshops employed an approach that ensured local knowledge and lived experiences were incorporated alongside scientific assessments, reflecting the co-production of knowledge in sustainability research (Turnhout et al. 2020; Voytenko et al. 2016).

In-depth interviews with key stakeholders

Semi-structured interviews were conducted with village heads, representatives from the Department of Marine and Fisheries, environmental NGOs, and academic partners. Interviews focused on institutional roles, decision-making processes, funding mechanisms, and socio-political challenges. All interviews were recorded with consent, transcribed, and thematically coded.

The participatory approach ensured that local knowledge and lived experiences were incorporated alongside scientific assessments, reflecting co-production of knowledge in sustainability research (Tribaldos et al. 2020). Ethical approval was granted by the Health Research Ethics Committee, Faculty of Public Health, Diponegoro University (No. 181/EA.KEPK-FKM/2025).

Data analysis

Seasonal differences in environmental parameters were analyzed using one-way ANOVA with Tukey post-hoc tests ($p < 0.05$). Pearson correlations assessed relationships between mangrove density and sediment accretion. Analyses were conducted in R 4.3.2. Qualitative and quantitative datasets were triangulated using Creswell's mixed-methods convergence framework to strengthen validity, identify consistencies or divergences, and integrate ecological and socio-cultural insights.

Results and discussion

Physico-chemical conditions

Significant seasonal differences were detected in salinity and pH (both $p < 0.01$), with lower values during the wet season due to increased freshwater inputs (Table 1). Salinity decreased from 29.34 ± 1.02 ppt (dry) to 23.18 ± 1.44 ppt (wet), while pH declined from 4.1 ± 0.26 to 3.2 ± 0.31. These patterns reflect monsoonal hydrology and are consistent with previous findings from

Table 1. Seasonal variation of water parameters in Bedono Village (Same Year, Different Seasons).

Parameter	Dry Season (Mean ± SD)	Wet Season (Mean ± SD)	ANOVA F-value	*p*-value
Salinity (ppt)	29.34 ± 1.02	23.18 ± 1.44	38.62	0.002
pH	4.1 ± 0.26	3.2 ± 0.31	24.77	0.004

northern Java mangrove–estuarine systems (Muskananfola et al. 2020; Soeprobowati et al. 2023). Reduced salinity during the wet season likely improved seedling establishment of *Rhizophora mucronata* and *Avicennia marina*, whereas the lower pH indicates enhanced organic decomposition and sulfide oxidation (Alongi 2015; Kristensen et al. 2008).

Sediment texture also shifted significantly (F = 21.47, p = 0.006), changing from sand-dominated (64%) in the dry season to a higher proportion of silt–clay material (43%) in the wet season (Table 2). This transition suggests increased sediment trapping by restored mangrove stands following NbS implementation.

Table 2. Sediment texture composition before and after NbS implementation.

Season	Sand (%)	Silt (%)	Clay (%)	ANOVA F-value	*p*-value
Dry (Pre-NbS)	64.3 ± 3.5	25.8 ± 2.1	9.9 ± 1.2	21.47	0.006
Wet (Post-NbS)	56.7 ± 4.1	31.2 ± 2.8	12.1 ± 1.5	—	—

Sediment texture analysis revealed that Bedono's substrate transitions from silty (72.4%) in the wet season to sandy-silt (48.7% silt, 41.2% sand) in the dry season, reflecting the interplay of hydrodynamic energy and sediment resuspension. These results are broadly consistent with the findings of Muskananfola et al. (2020), who reported in March, the sediment is predominantly silt (85.78%), while in October, it is more sandy (40.13%). This variation influences the distribution and abundance of mangrove species, as different species have varying tolerances to salinity levels (Meera et al. 2023). The organic material content in the sediment remains relatively stable between seasons (14.95% in March and 14.65% in October) (Muskananfola et al. 2020). Organic matter is crucial for providing nutrients to mangrove species, influencing their growth and distribution (Meera et al. 2023). Different mangrove species exhibit varying levels of tolerance to environmental stressors. For instance, species like *Avicennia marina* and *Rhizophora mangle* have shown different growth responses to salinity and light levels, with some species being more sensitive to high salinity and light conditions (Liao et al. 2025).

Seasonal sediment dynamics showed coarser, sand-dominated substrates in the dry season due to higher tidal energy and reduced freshwater discharge, while the wet season increased silt–clay deposition, enhancing nutrient retention, carbon burial, and seedling establishment. The shift from 64.3% sand to 56.7% sand alongside higher silt–clay fractions after NbS implementation indicates improved sediment trapping and reduced erosion, consistent with increased mangrove density and canopy complexity that slow water flow and promote fine-particle deposition (Alongi 2014; Bhomia et al. 2016). Sediment accretion correlated strongly with mangrove density (r = 0.91, p = 0.012), with

dense *Rhizophora mucronata* stands facilitating tidal attenuation and accumulation of finer, organic-rich material, thereby strengthening coastal stability and vertical accretion.

Mangrove density

Mangrove density showed a strong positive correlation with sediment accretion ($r = 0.91$, $p = 0.012$; Table 3), indicating that denser stands enhanced sediment retention and stabilization. Higher stem densities corresponded to greater accretion rates, providing quantitative evidence that NbS-based restoration improves sediment stability and coastal resilience in Bedono.

Combined shifts in salinity, pH, and sediment texture demonstrate that NbS interventions significantly influence hydrological and geomorphological conditions. Restored mangrove cover acts as a bio-physical buffer that reduces salinity intrusion, increases fine sediment trapping, and moderates pH fluctuations—key benefits for systems facing sea-level rise and land subsidence. Continuous physicochemical monitoring and seasonally informed restoration planning would further strengthen adaptive NbS management.

Table 3. Mangrove stand density and sediment accretion rate in monitoring plots.

Plot	Mangrove Density (stems m^{-2})	Sediment Accretion (cm yr^{-1})
P1	3.8	1.4
P2	4.1	1.6
P3	4.3	1.7
P4	4.8	2.0
P5	5.2	2.3

Overall, the interaction of seasonal salinity dynamics, acidic but biogeochemically active soils, and progressive sediment fining reflects improving habitat conditions that support sustainable mangrove rehabilitation under NbS implementation.

Mangrove condition

Mangrove assessments identified *Avicennia marina*, *A. alba*, and *Rhizophora mucronata* as the dominant species in Bedono (Table 4). Following NbS interventions—primarily community-based restoration and hydrological reconnection—mangrove structure improved markedly. Total density increased from 75 to 149 individuals per 100 m^2, with *A. marina* remaining dominant due to its tolerance to salinity and periodic inundation. *R. mucronata* showed substantial recovery, rising from 28 to 59 individuals per 100 m^2 with a 68% seedling survival rate, particularly in sheltered areas. *Sonneratia alba* exhibited a lower survival rate (54%) consistent with its sensitivity to wave exposure.

Species diversity increased significantly, indicated by the rise of the Shannon Index from 0.83 to 1.47, reflecting improved habitat heterogeneity and ecosystem resilience. These changes demonstrate the effectiveness of NbS in enhancing structural complexity and promoting natural regeneration in subsiding coastal environments.

Table 4. Changes in mangrove community structure before and after NbS implementation in Bedono Village.

Species	Pre-NbS Density (ind./100 m²)	Post-NbS Density (ind./100 m²)	Seedling Survival Rate (%)	Remarks
Avicennia marina	35	68	72	High tolerance to salinity; dominant colonizer
Rhizophora mucronata	28	59	68	Successful establishment in sheltered areas
Sonneratia alba	12	22	54	Lower survival in wave-exposed zones
Total individuals	75	149	—	—
Species richness (S)	3	3	—	—
Shannon Diversity (H')	0.83	1.47	—	Increased diversity and structural complexity

The post-restoration increase in density and diversity supports the ecological benefits of hydrological reconnection and mixed-species planting. Survival patterns aligned with known ecological traits: high tolerance of *A. marina*, substrate stability requirements of *R. mucronata*, and wave sensitivity of *S. alba*. Enhanced diversity improves ecosystem functioning, nutrient cycling, and carbon sequestration potential, aligning with findings from other Java north-coast restoration sites where ecological engineering and community engagement reduced coastal vulnerability.

Overall, Bedono's NbS outcomes highlight the value of coupling ecological suitability with local stewardship, illustrating how adaptive management can restore mangrove ecosystem functionality and increase resilience in dynamic deltaic settings.

Socio-economic impacts

Primary records from the Bedono Village Office indicate that approximately 30 houses are loss each year as a result of progressive land subsidence and tidal intrusion, a trend that continuous to escalate. These data, derived from official inundation and relocation records between 2018 and 2025, represent the administrative count of households affected by coastal flooding. Field observations documented a progressive loss of coastal housing in Bedono Village over the past four years (Fig. 2).

In 2022, the last remaining house closest to the shoreline was still intact and still inhabitated by Mrs. Paijah, a long-term resident who had lived through successive inundation events access to the house was possible only via a narrow bamboo bridge, as seawater had already inundated the ground beneath.

By 2023, the house had been completely lost to coastal inundation, marking the disappearance of the final habitable structure in that section of the village. Measurements and visual assessments conducted in 2024 indicated a further rise in seawater levels at the site, a trend that persisted into 2025. This pattern reflects the combined effects of land subsidence, tidal flooding, and coastal erosion have resulted in both physical and socio-economic displacement, with affected households forced to relocate inland or migrate to neighboring areas.

Figure 2. Bedono village from 2022–2025.

This condition underscoring the urgency of implementing and scaling NbS to reduce future risk. Analysis of spatial imagery showed significant shoreline advancement in areas where mangrove restoration had been actively pursued (Soeprobowati et al. 2025).

Over 90% of respondents perceived worsening tidal inundation and land loss over the past decade, while also acknowledging that mangrove planting has helped reduce flooding impacts. Participation in restoration was high, with 76% involved in mangrove planting since 2020 and 67% of women engaged in NbS-based enterprise training. Perceived economic benefits were moderate but positive, reflected in a mean Likert score of 3.9 ± 0.9 for the statement "NbS activities have improved household income."

Triangulation of survey responses, interviews, and environmental data revealed strong agreement between community perceptions and measured ecosystem conditions. Among 45 participants, 85% reported reduced erosion and improved fish catch following restoration—patterns supported by field data showing salinity of 20.47–31.62 ppt, acidic pH of 2.5–4.4, and fine, organic-rich sediments suitable for mangrove growth (Table 1; Figs 2, 3). Community observations of increased biodiversity and improved water quality also aligned with measured ecological responses. Minor discrepancies, particularly regarding short-term water quality fluctuations, highlight the need for continued monitoring to sustain NbS outcomes.

Figure 3. Socioeconomic impact of diurnal daily tides in Bedono Village. **A.** Daily tidal inundation to which residents have adapted; ***B.*** Ongoing land subsidence leading to full community relocation; **C.** The village mosque affected by rising water levels; **D.** The elementary school similarly impacted.

The integration of stakeholder knowledge with quantitative measurements demonstrates that NbS interventions are enhancing both ecosystem health and community well-being. These triangulated findings offer a strong basis for adaptive management and support broader evidence on the value of co-produced knowledge and inclusive governance in coastal restoration (Figs 2–4; Table 1).

Diurnal tidal flooding and coastal resilience

Diurnal tidal flooding in Bedono occurs when high tides inundate coastal areas, often exacerbated by sea-level rise and storm surges. These recurrent flooding events have led to substantial socio-economic impacts, including damage to infrastructure, displacement of communities, loss of residential areas, and displacement of coastal communities (Fig. 3).

Sediment accretion and vegetation cover were positively correlated, indicating that mangrove density played a key role in stabilizing coastal zones. This not only supports climate resilience but also enhances the natural regeneration capacity of surrounding habitats.

Field measurements and spatial analyses showed a clear positive relationship between vegetation cover and sediment accretion, confirming that man-

Figure 4. Implementation of NbS includes coastal vegetation restoration, managed realignment, and the conservation of mangroves from all components.

grove density is a key driver of coastal stabilization. Well-developed stands of *Avicennia marina* and *Rhizophora mucronata* accumulated more sediment. They experienced less erosion than sparsely vegetated or degraded areas, underscoring the role of mangrove-based NbS in enhancing climate resilience and supporting natural regeneration.

Diurnal tidal flooding in Bedono reflects the combined effects of natural coastal dynamics and human-driven land subsidence. Increasingly frequent and prolonged high-tide inundation—exacerbated by sea-level rise, groundwater extraction, and reduced sediment supply—has converted extensive areas into intertidal flats. The socio-economic impacts are severe, including progressive land loss, disruption of livelihoods, and ongoing displacement of households.

Sediment–vegetation dynamics and the role of NbS

Sediment characteristics in Bedono strongly reflect interactions with mangrove cover. Well-established stands of *Avicennia marina* and *Rhizophora mucronata* accumulated higher proportions of fine sediments. They showed greater accretion, consistent with the ability of mangrove root systems to trap particles, stabilize soils, and reduce erosion. In contrast, sparsely vegetated or degraded zones retained coarser, sandier sediments and exhibited higher erosion potential, illustrating the reinforcing feedback between vegetation structure and geomorphic stability.

Restoration efforts further strengthened this relationship: sediment accretion rates increased in areas with higher mangrove density, and seedling survival exceeded 70% in sheltered sites. These outcomes demonstrate the effectiveness of mangrove-based NbS in enhancing shoreline stability, supporting blue carbon sequestration, and improving habitat quality for adjacent aquaculture systems.

Implications for adaptation and policy

Bedono's combined sediment–vegetation monitoring and community-based observations provide a robust foundation for adaptive coastal management. Policies emphasizing mangrove rehabilitation, regulated aquaculture zoning, and reduced groundwater extraction are essential to slow subsidence and curb ongoing inundation. Effective implementation requires coordination across local government, scientific institutions, and community groups to sustain long-term NbS initiatives.

Broader significance

The Bedono case illustrates how mangrove ecosystems function as natural buffers against tidal flooding and shoreline retreat in subsiding deltaic environments. The integration of biophysical measurements with socio-economic data offers strong empirical support for NbS as a viable strategy to mitigate the coupled ecological and social impacts of coastal change. This approach provides a transferable model for other low-lying tropical coasts facing similar pressures.

Socio-economic Co-benefits of nature-based solutions

In addition to ecological outcomes, the implementation of NbS in Bedono has generated tangible social benefits. Local communities have been actively involved in mangrove planting, facilitated by educational institutions and non-governmental organizations (Fig. 4). Thematic student internships have supported environmental education, while training programs for women have promoted

economic diversification through the development of mangrove-based products, including syrup, cookies, and natural dyes. These activities have strengthened environmental stewardship and improved household income.

The involvement of students and youth through thematic internships and community service programs has strengthened environmental literacy and facilitated knowledge exchange between universities and local communities. Simultaneously, women's empowerment initiatives have diversified livelihoods through mangrove-based enterprises—such as syrups, cookies, batik dyes, and handicrafts—which supplement household income and reinforce the social sustainability of restoration efforts.

Community engagement, youth participation, and women's empowerment in mangrove restoration

Community participation has become a central pillar of mangrove restoration in Bedono, integrating academic, social, and economic dimensions into a cohesive local strategy. The involvement of students and youth—through thematic internships, field courses, and community service (KKN) programs—has significantly enhanced environmental literacy and fostered two-way knowledge exchange between academic institutions and coastal residents. These activities not only provide scientific support for restoration monitoring but also empower young people to become advocates for coastal resilience within their own communities.

At the same time, women's empowerment initiatives have strengthened the socio-economic foundation of restoration efforts. Training and community-based enterprises centered on mangrove-derived products—such as syrups, cookies, batik dyes, herbal preparations, and handicrafts—have diversified livelihood opportunities for local households. These initiatives reduce economic vulnerability while increasing community ownership of restoration activities. By linking ecological recovery with tangible economic benefits, women's groups contribute to the long-term social sustainability of mangrove rehabilitation and help ensure that restored ecosystems continue to be valued, protected, and integrated into local development pathways.

These outcomes illustrate the multi-dimensional value of NbS, contributing to national goals for climate adaptation and the Sustainable Development Goals (SDGs 13, 14, and 15). Continued success will require sustained monitoring, institutional support, and the integration of hydromorphological modeling and remote sensing to track carbon sequestration, sedimentation rates, and shoreline change.

Implications for policy and sustainable development

The findings from Bedono highlight the importance of integrating local knowledge, community participation, and ecosystem-based approaches into Indonesia's coastal management and sustainable development agenda. Beyond the ecological benefits of improved mangrove growth, sediment stabilization, and enhanced carbon storage, community engagement in restoration—through youth involvement, local knowledge, and women-led enterprises—strengthens stewardship and increases the social acceptance of climate adaptation mea-

sures. To translate these outcomes into broader policy relevance, NbS should be mainstreamed into coastal planning instruments such as RZWP3K, ensuring that mangrove rehabilitation and sediment management align with ecosystem functions and livelihood needs. Institutionalizing community-based monitoring, supported by universities and government agencies, would improve data continuity and adaptive management. Likewise, targeted incentives for women and youth, including training and microenterprise development, can enhance economic resilience while sustaining the gains from restoration. Integrating NbS into national adaptation and disaster risk reduction frameworks (RAN-API and RAN-PRB) would reinforce Indonesia's commitments to the Paris Agreement and the Sustainable Development Goals. Finally, expanding successful Living Lab models—such as the one established in Bedono—offers a scalable pathway for strengthening policy coherence, innovation, and community-driven climate adaptation in other vulnerable coastal regions.

Community-based mangrove rehabilitation in Bedono demonstrates how local participation strengthens the long-term effectiveness of NbS. Local knowledge, cultural traditions, and community-led stewardship have contributed to improved mangrove survival, shoreline stabilization, and sediment carbon accumulation. These outcomes are comparable to other Indonesian and international restoration sites (Table 5), indicating that co-managed NbS approaches can generate robust ecological and social co-benefits (Chow 2018; Basyuni et al. 2022).

Across sites, Bedono's estimated mangrove survival rates (60–80%, depending on hydrodynamic exposure) align with community-led restoration results in Bangladesh's Sundarbans (50–85%) and Vietnam's storm-prone mangroves (55–75%) (Chow 2018). Bedono's trajectory of sedimentary carbon recovery also fits within regional blue-carbon ranges reported for Southeast Asia (Sasmito et al. 2020), suggesting that properly situated mangrove NbS can meaningfully contribute to climate mitigation even in subsiding coastal systems.

Social outcomes in Bedono—including increased stewardship and improved local livelihoods—mirror findings from other community-driven mangrove initiatives in Demak and North Sumatra, where involvement in planning and maintenance has been shown to enhance project longevity and reduce replanting failure (Muskananfola et al. 2020; Basyuni et al. 2022). Comparable international cases also report substantial livelihood benefits from fisheries enhancement, ecotourism, and sustainable resource use (Chow 2018).

Collectively, the comparison across sites (Table 5) emphasizes that effective mangrove restoration requires approaches that match environmental conditions with community governance structures. The Bedono case provides a practical example of how culturally embedded NbS can support Indonesia's FOLU Net Sink 2030 target and deliver multiple SDG outcomes, especially SDG 13 (Climate Action), SDG 14 (Life Below Water), and SDG 15 (Life on Land).

Between 2022 and 2025, Bedono exhibited clear ecological and social improvements following the implementation of NbS, beginning with intensified tidal flooding and initial mangrove recolonization in 2022, followed by rapid seedling expansion and sediment accumulation in 2023. By 2024, increasing canopy cover and formalized community monitoring indicated a transition toward ecosystem recovery, culminating in 2025 with more stable mangrove stands and emerging livelihood opportunities (Table 6).

Table 5. Comparative analysis of mangrove restoration outcomes in Indonesia and abroad.

Location	Restoration approach	Reported survival rate	Economic / Social benefits
Bedono, Indonesia	Hybrid engineering (permeable structures) + strong community engagement	60–80% (estimated; comparable Java cases)	Improved coastal protection; strengthened local stewardship; livelihood diversification
Demak, Indonesia	Permeable dams + community monitoring (Bio-rights model)	70–85%	Reduced erosion; increased fisheries income (Muskananfola et al. 2020)
North Sumatra, Indonesia	Community-based planting + enrichment	65–80%	Carbon sequestration gains; increased household participation (Basyuni et al. 2022)
Makassar, Indonesia	Bamboo wave breakers + bed construction	70–90%	Stabilization of agricultural lands valued at ~USD 18.8 billion (Armono et al. 2022)
Sundarbans, Bangladesh	Community-led planting and protection	50–85%	Tourism valuation ~USD 53 million annually (Chow 2018)
Brazil mangrove	Integrated aquaculture with natural ecosysytem, such as mangrove	55–75%	Coastal defense and increased aquaculture productivity (de Lacerda et al. 2020)

Table 6. Timeline of Bedono's Changes (2022–2025).

Year	Key events
2022	Increased frequency of tidal flooding
	Initial mangrove recolonization efforts
	Community meetings on relocation and adaptatiom
2023	Expansion of mangrove seedlings
	Sediment accretion behind structures
	Strengthened local stewardship
2024	Improved mangrove canopy cover
	Formalized community monitoring
	Enhanced community cohesion
2025	More stable mangrove stands
	Emerging livelihood opportunities
	Progress towards long-term management

These outcomes reflect a sequential NbS process—problem identification, community consultation, site assessment, hybrid engineering installation, mangrove planting, monitoring, livelihood integration, and long-term governance—which collectively generated socio-economic benefits (Fig. 5). These include small but meaningful income from seedling nurseries and mangrove-based products, reduced wave impacts on remaining infrastructure, improved fish and crab availability, enhanced community cohesion through shared stewardship, and the continued expression of local environmental traditions (Table 7).

The Bedono model demonstrates high transferability to other subsiding and erosion-prone coastlines, particularly where community capacity and hybrid engineering can be jointly developed. Key elements—such as community-based mangrove nurseries, participatory monitoring, and the use of permeable brushwood barriers to stimulate sediment accretion—can be adapted to local geomorphic conditions. Policy mechanisms can further enhance replication, including incentives for silvofishery adoption, support for village-led restoration

Figure 5. NbS implementation in Bedono, Demak, Central Java.

Table 7. Socio-economy benefit.

Category	Benefit
Livelyhoods	Income from seedling nurseries and mangrove products
Coastal protection	Reduce wave damage and shoreline stabilization
Food security	Increased mussel populations
Social well-being	Stronger community cohesion and participation

enterprises, and alignment with provincial coastal zoning plans. By combining ecological rehabilitation with socio-economic empowerment, the Bedono experience provides a practical template for scaling NbS and hybrid measures across Indonesia's northern coast and similar deltaic environments.

Limitations

This study acknowledges several limitations that should be considered when interpreting its findings. First, community perceptions and responses were derived from self-reported interviews, which may be subject to recall bias or social desirability effects. Although triangulated with observational and biophysical data, these subjective elements may influence the nuance of socio-cultural insights. Second, the environmental datasets—especially those related to mangrove growth, sediment accretion, and tidal inundation—were collected primarily between 2022 and 2025. While these data provide an important snapshot of current ecological conditions, longer-term monitoring is required to capture interannual variability and the cumulative effects of subsidence and sea-level rise. Despite these constraints, the integration of quantitative measurements, qualitative interviews, and participatory observations strengthens the internal validity and reliability of the overall findings.

Conclusion

The Bedono case demonstrates that integrating Nature-based Solutions with hybrid engineering offers an effective and context-sensitive pathway for strengthening resilience in subsiding and tidally flooded estuarine landscapes. The use of permeable brushwood barriers constructed from bamboo and mangrove branches has proven particularly effective in Demak, where these structures

attenuate wave energy, stimulate sediment accretion of approximately 5–15 cm per year, and create favourable conditions for the natural recruitment of *Avicennia* and *Rhizophora*. When combined with community-led mangrove rehabilitation, these hybrid measures have contributed to shoreline stabilization and improved ecosystem functionality. At the same time, active participation from youth, women, and local community groups has supported livelihood diversification and reinforced environmental stewardship, linking ecological gains to social benefits. These outcomes highlight the ability of NbS and bamboo-based hybrid engineering to deliver multi-dimensional co-benefits that advance local climate adaptation priorities, human well-being, and sustainable coastal management. The Bedono model provides a replicable framework for other vulnerable coastlines across Indonesia and the Global South, underscoring the need for long-term monitoring, institutional support, and policy incentives—such as silvofishery integration—to sustain restoration benefits and scale successful approaches.

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Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statement

Ethical approval was granted by the Health Research Ethics Committee, Faculty of Public Health, Diponegoro University (No. 181/EA.KEPK-FKM/2025).

Use of AI

AI was used to help with grammar and strengthen the English.

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Data availability

All of the data that support the findings of this study are available in the main text.

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